UED

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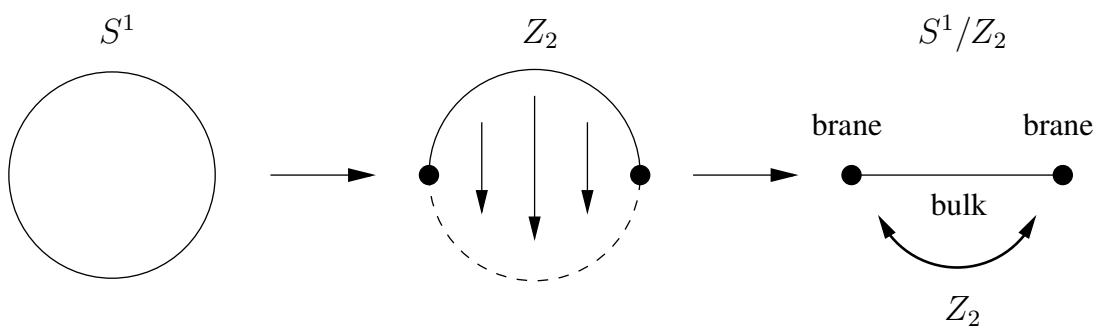
Overview on UED

- Universal: all SM particles in flat ED
- The simplest model: S1/Z2 (5D)
- KK-parity:
  - all SM particles (zero mode) are even
  - level 1 KK particles (n=1) are odd
  - level 2 KK particles (n=2) are even
  - electroweak precision constraints are avoided
    - new contributions are loop-suppressed
  - the LKP is stable and a DM candidate

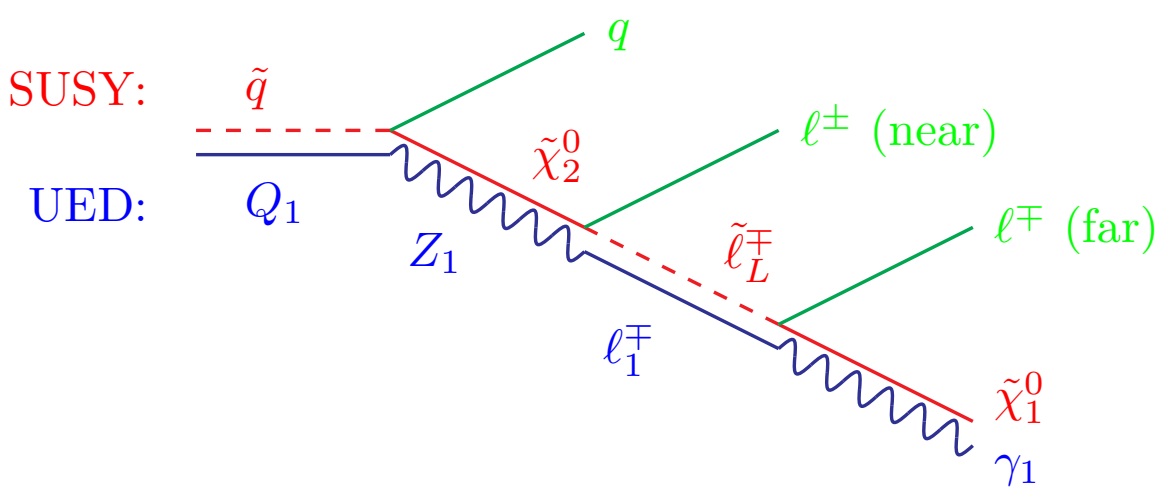


Universal Extra Dimensions

- MUED: Minimal Universal Extra Dimensions (cf. mSugra)
- 2UED: Two Universal Extra Dimensions (GMSB)
- nUED: non-minimal Universal Extra Dimensions
  - boundary terms
- SUED: Split Universal Extra Dimensions (cf. Split SUSY)
  - bulk terms
- sUED: UED with singlet extension
- NMUED: Next-to-Minimal UED
  - (with boundary and bulk terms)

More on UED

- Minimal UED: mass splitting be generated by radiative corrections (assuming no boundary terms and no bulk masses)
- Short RG running leads to compressed mass spectrum
- Larger production cross sections (compared to SUSY productions), i.e., KK gluon, KK quark productions
- SUSY-like cascade decays at the LHC from the first KK modes.

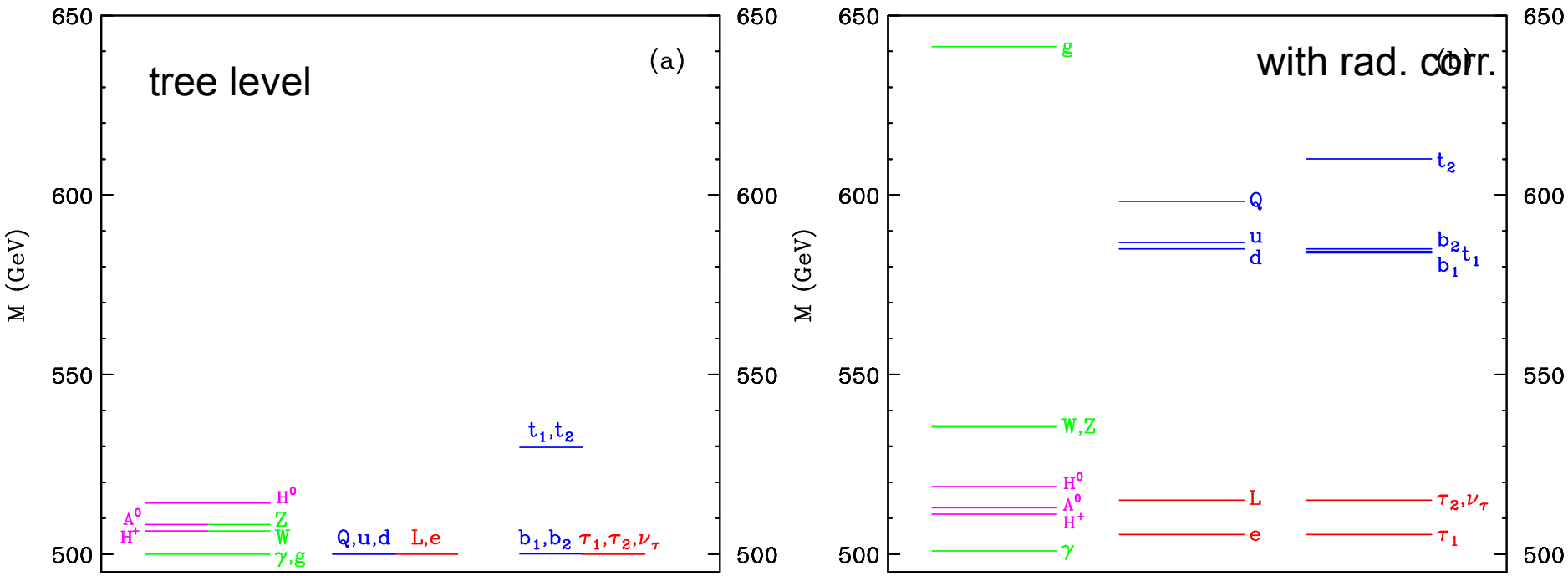


- Distinct feature: 2nd KK modes...

Minimal UED

- Two parameters: R, Lambda (cutoff)

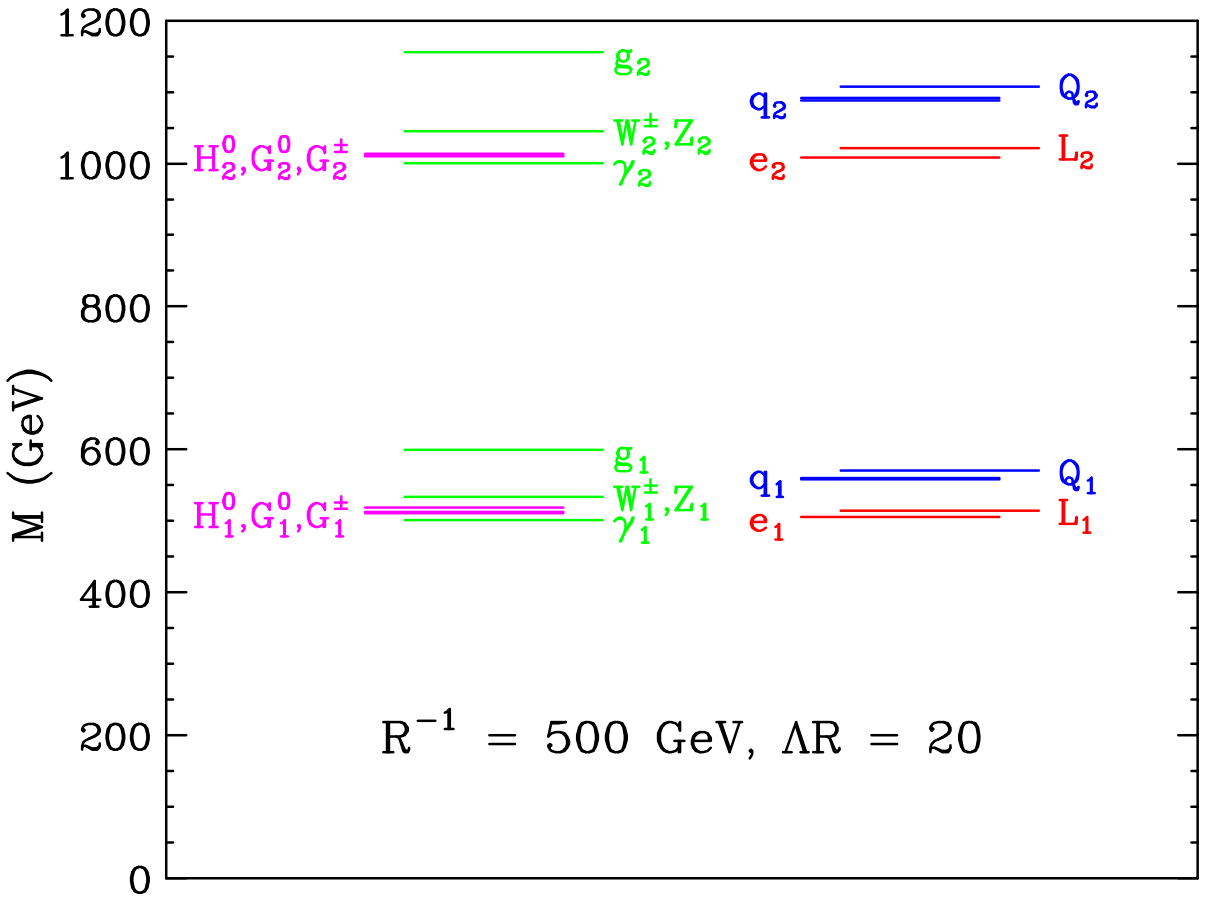
Cheng, Matchev, Schmaltz, 2002



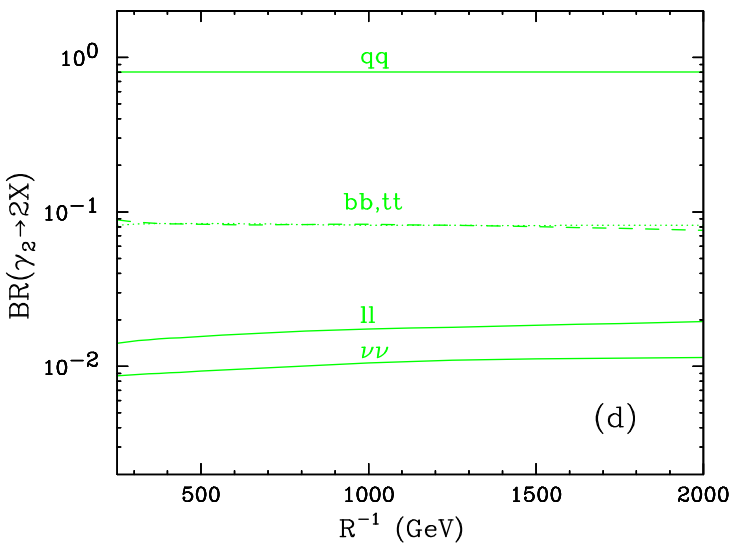
Minimal UED

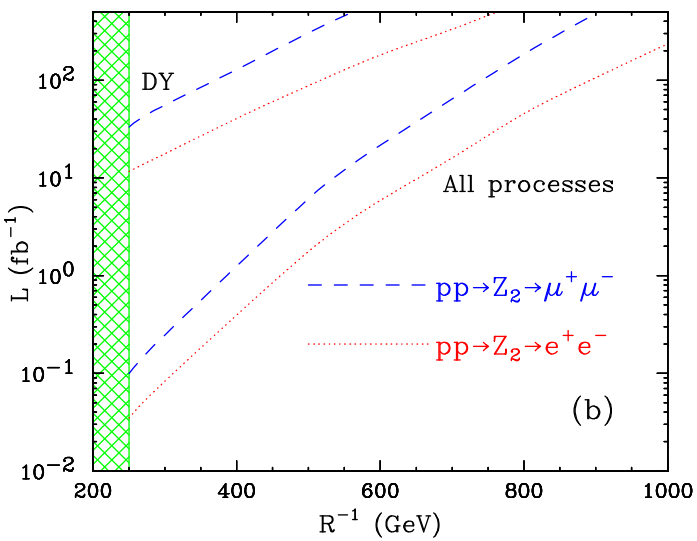
- Two parameters: R, Lambda (cutoff)

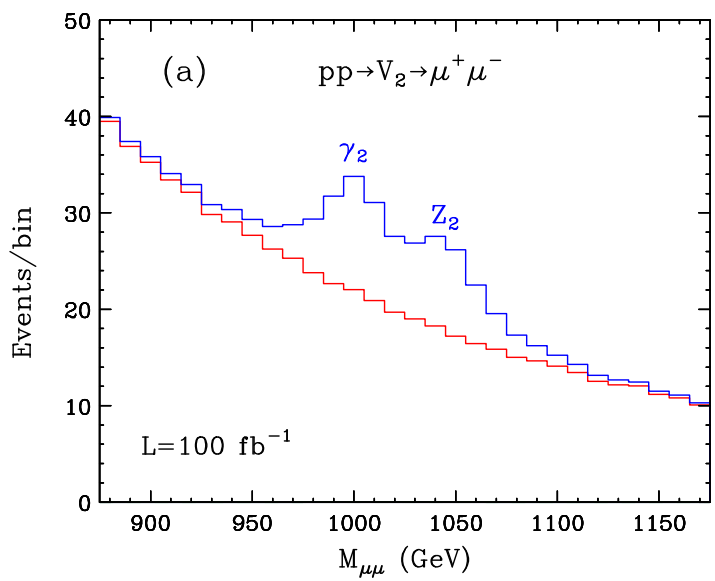
Cheng, Matchev, Schmaltz, 2002

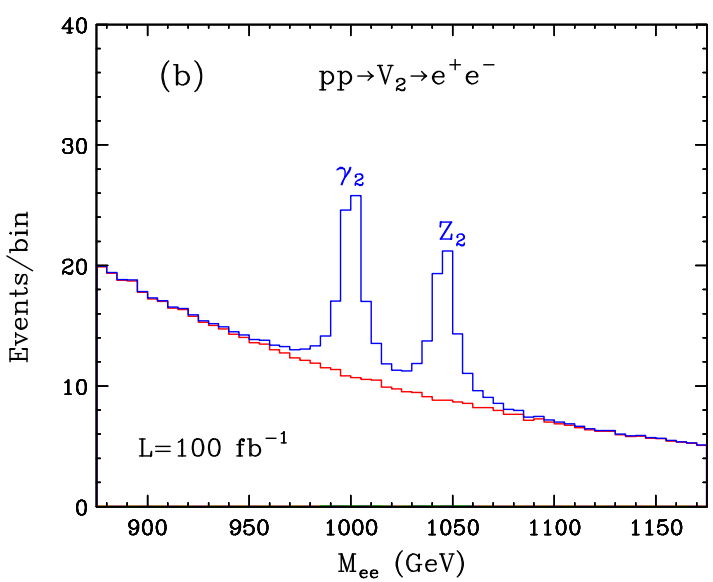


Level 2: KK resonances







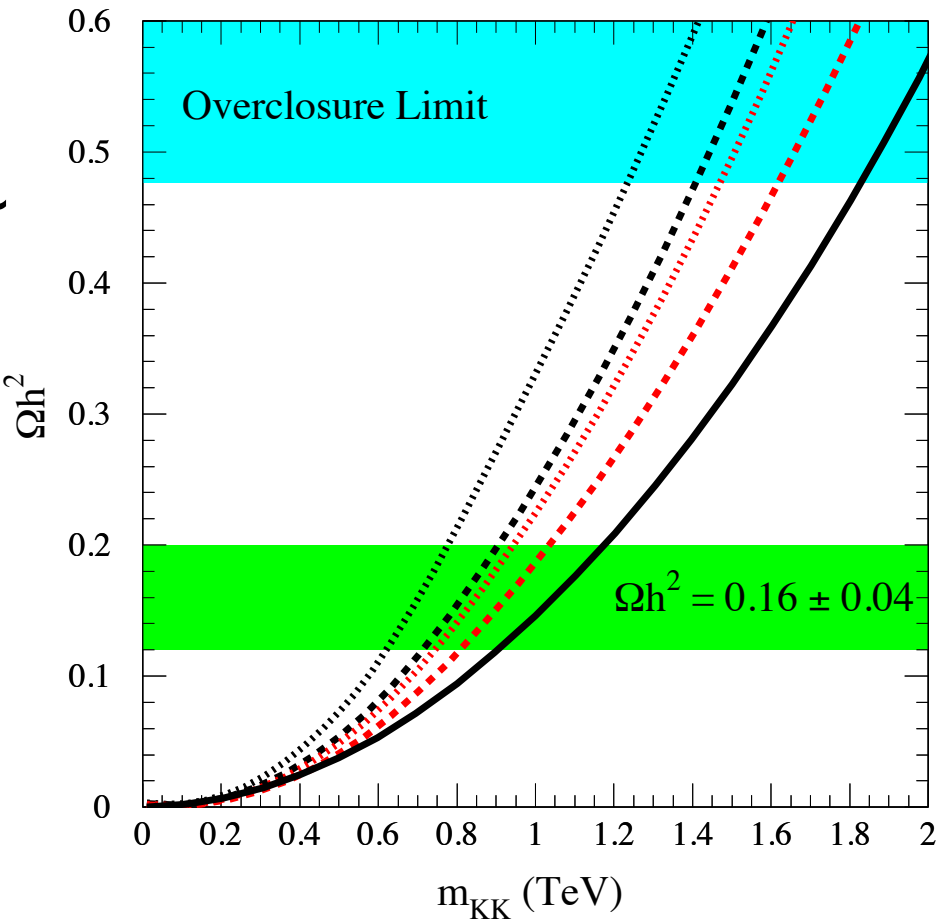


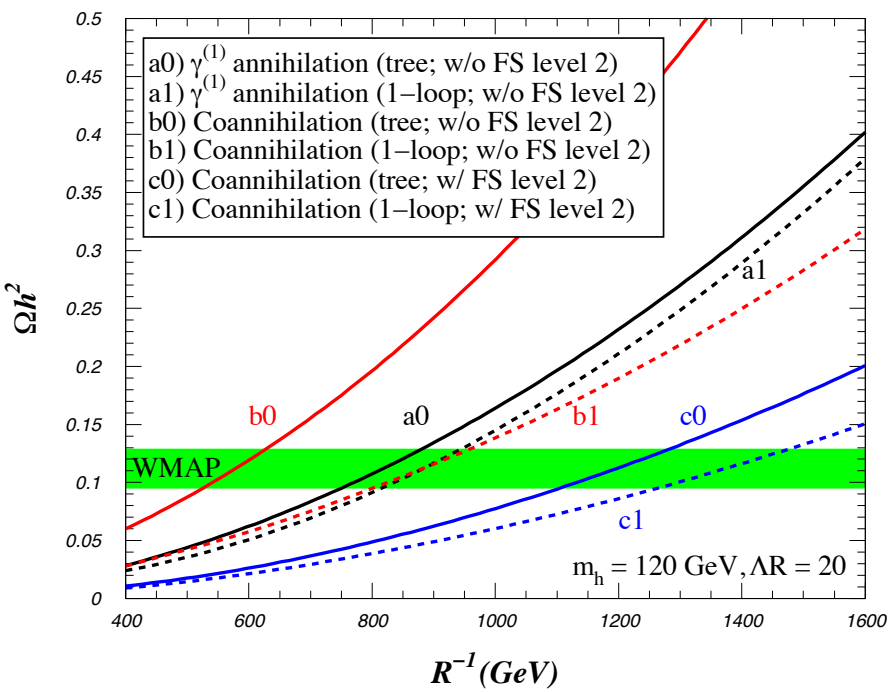
Datta, Kong, Matchev 2005

KK Dark Matter: abundance

- O(1) TeV KK photon
- Coannihilation with SU(2)-singlet KK leptons lowers LKP mass to ~ 600 GeV.

Servant, Tait 2002



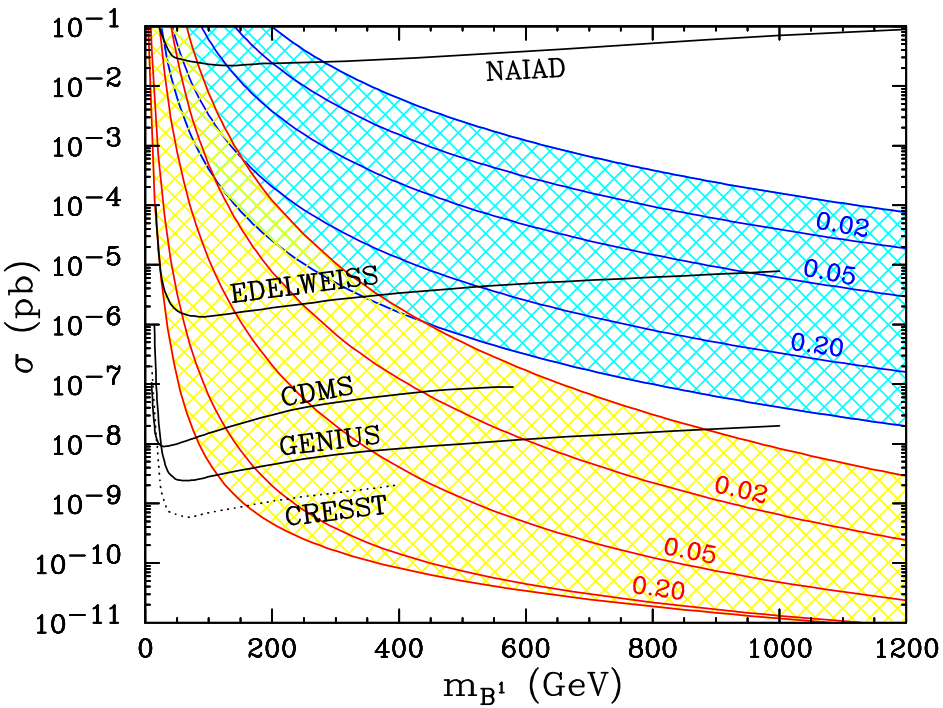


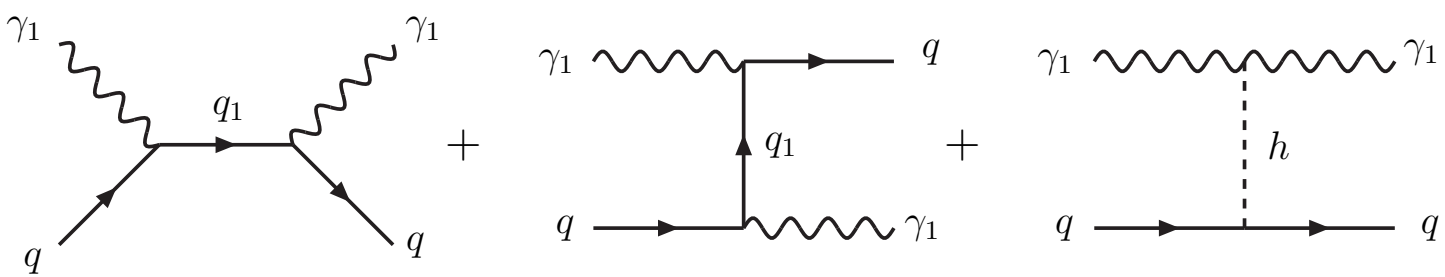
Belanger, Kakizaki, Pukhov, 2010

KK Dark Matter: direct detection

- Direct detection hard
- Treat mass splitting as a free parameter (better chance for direct detection)

Cheng, Feng, Matchev 2002

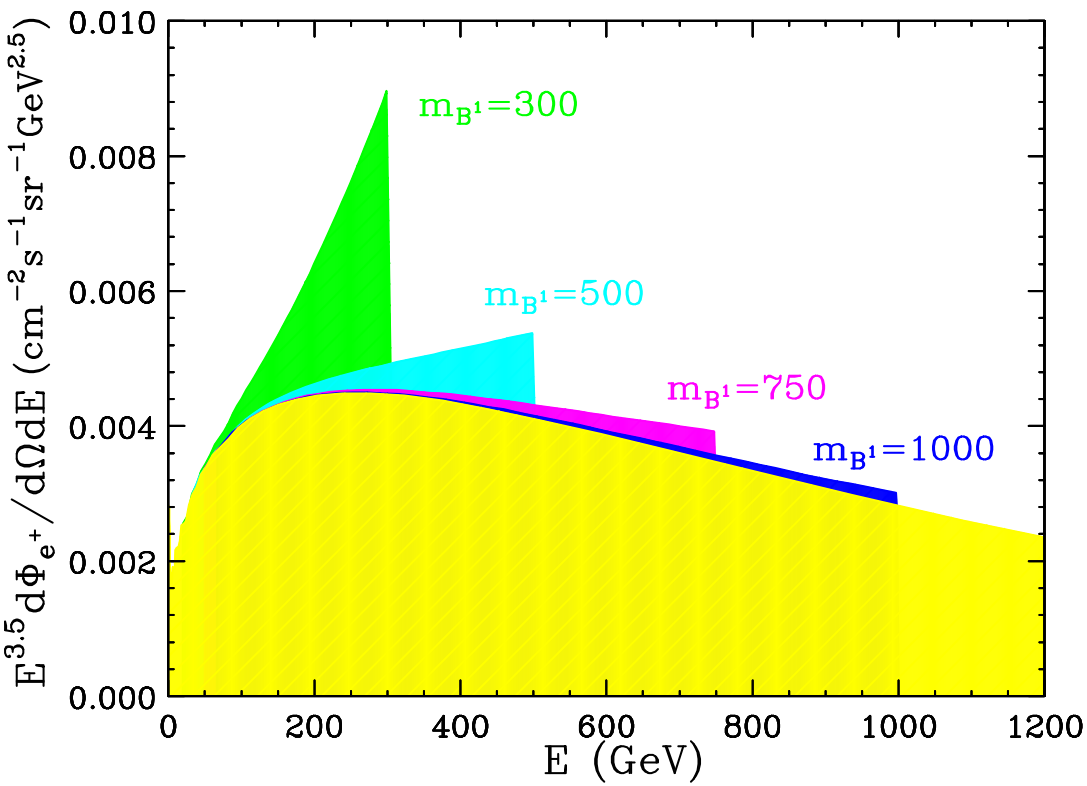




KK Dark Matter: indirect detection

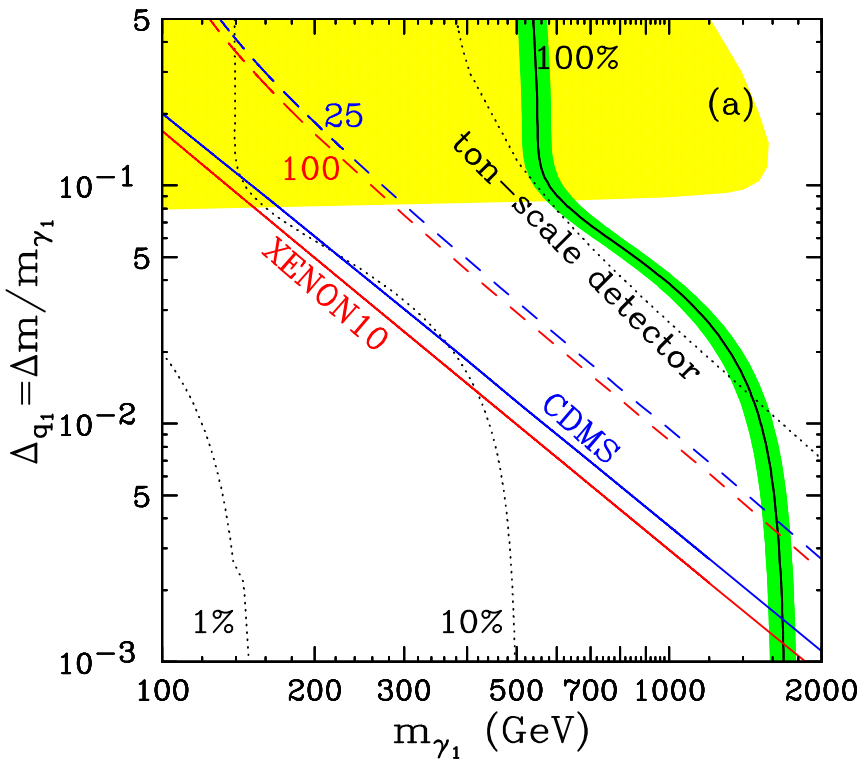
- Indirect detection: lepton final states, positron/neutrino/photon flux

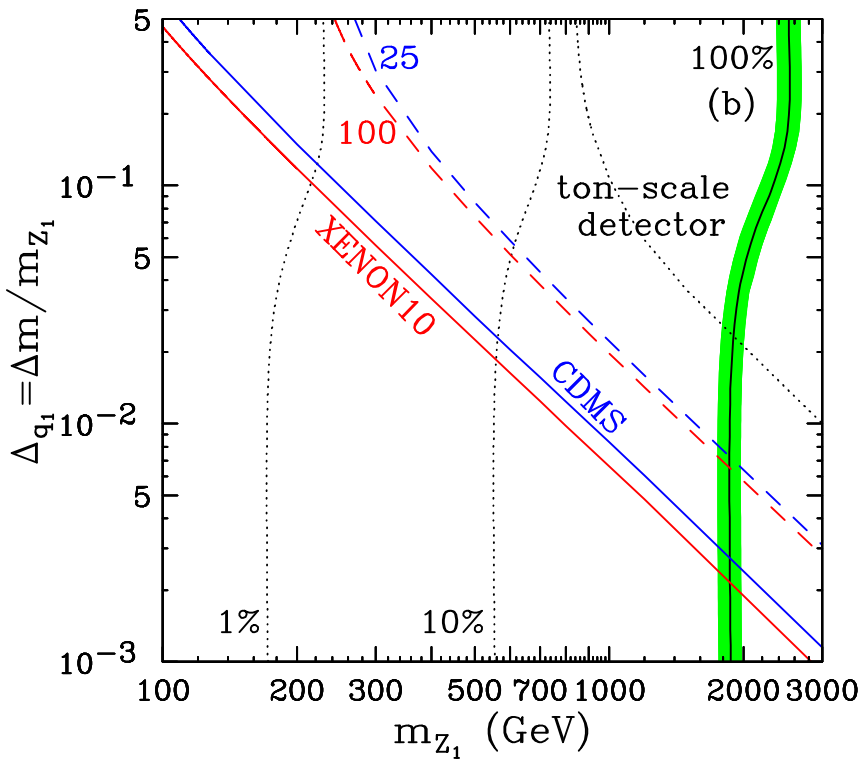
Cheng, Feng, Matchev 2002



KK Dark Matter: complementarity

- Treat the LKP mass and mass splitting as free parameters.
- Gives a better chance for the LHC, and direct detection.



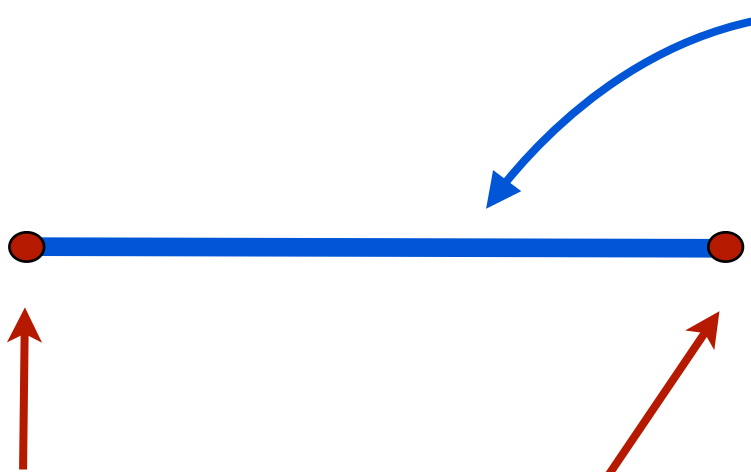


- Yellow: 4 leptons plus MET at 14 TeV LHC with 100 fb-1
- Green: relic abundance

Arrenberg, Baudis, Kong, Matchev, Yoo 2008

NMUED

Flacke, Kong, Park 2013



$$S_5 = \int d^4x \int_{-L}^{L} dy \, [\mathcal{L}_V + \mathcal{L}_\Psi + \mathcal{L}_H + \mathcal{L}_{Yuk}]$$

$$\mathcal{L}_V = \sum_{\mathcal{A}}^{G,W,B} -\frac{1}{4}\mathcal{A}^{MN} \cdot \mathcal{A}_{MN}$$

$$\mathcal{L}_\Psi = \sum_{\Psi}^{Q,U,D,L,E} i\overline{\Psi}\overleftrightarrow{D}_M\Gamma^M\Psi - M_\Psi\overline{\Psi}\Psi$$

$$\mu\theta(y) = M_{Q,L} = -M_{U,D,E}$$

$$M_\Psi(y) = -M_\Psi(-y)$$

$$\mathcal{L}_{\partial V} = \sum_{\mathcal{A}}^{G,W,B} -\frac{r_{\mathcal{A}}}{4}\mathcal{A}_{\mu\nu} \cdot \mathcal{A}^{\mu\nu},$$

$$\mathcal{L}_{\partial\Psi} = \sum_{\Psi=Q,L} i r_\Psi \overline{\Psi}_L D_\mu \gamma^\mu \Psi_L + \sum_{\Psi=U,D,E} i r_\Psi \overline{\Psi}_R D_\mu \gamma^\mu \Psi_R,$$

$$\mathcal{L}_{\partial H} = r_H \left(D_\mu H\right)^\dagger D^\mu H + r_\mu \mu_5^2 |H|^2 - r_\lambda \lambda_5 |H|^4 \,,$$

$$\mathcal{L}_{\partial Yuk} = r_{\lambda^E}\lambda_5^E \overline{L} H E + r_{\lambda^D}\lambda_5^D \overline{Q} H D + r_{\lambda^U}\lambda_5^U \overline{Q}\tilde{H} D + \text{h.c.}$$

$$\mathcal{L}_H = \left(D_M H\right)^\dagger D^M H - V(H),$$

$$V(H) = -\mu_5^2 |H|^2 + \lambda_5 |H|^4 \,,$$

$$\mathcal{L}_{Yuk} = \lambda_5^E \overline{L} H E + \lambda_5^D \overline{Q} H D + \lambda_5^U \overline{Q}\tilde{H} D + \text{h.c.}$$

$$S_{bdy} = \int d^4x \int_{-L}^{L} dy \, \left(\mathcal{L}_{\partial V} + \mathcal{L}_{\partial\Psi} + \mathcal{L}_{\partial H} + \mathcal{L}_{\partial Yuk}\right) [\delta(y-L) + \delta(y+L)]$$

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fermion bulk masses $M_{Q,U,D,L,E}$

boundary gauge parameters r_G, r_W, r_B

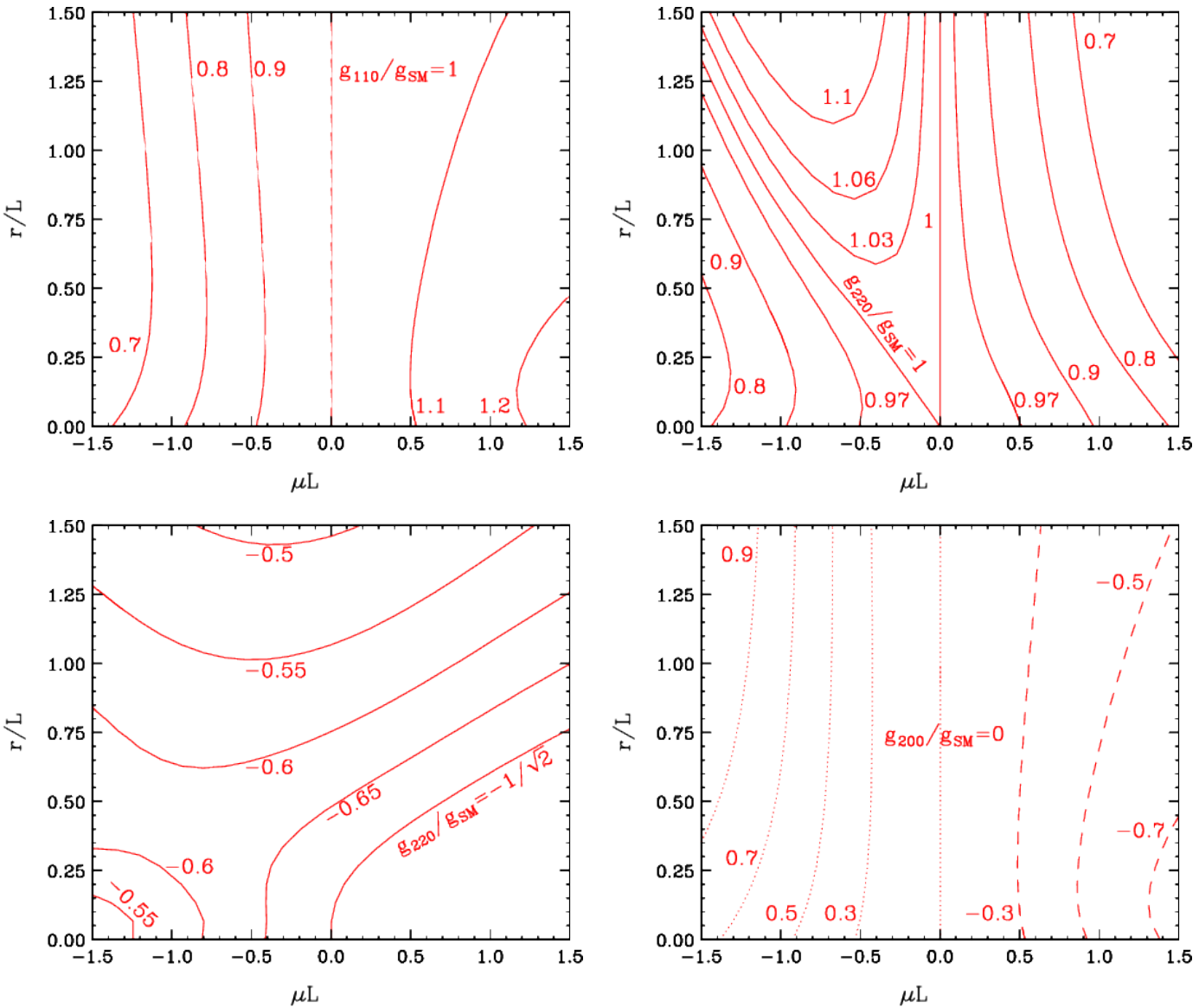
boundary Higgs parameters r_H, r_μ, r_λ

boundary fermion parameters $r_{Q,U,D,L,E}$

boundary Yukawa couplings $r_{\lambda^{U,D,E}}$

- To avoid tree-level FCNC, set all M and r flavor blind -> 19.
- For $r_\mu \neq r_\lambda$, bulk VEV and boundary VEV different.
- To avoid KK mode mixing, set all r's the same.
- Assume universal bulk masses.

NMUED: couplings



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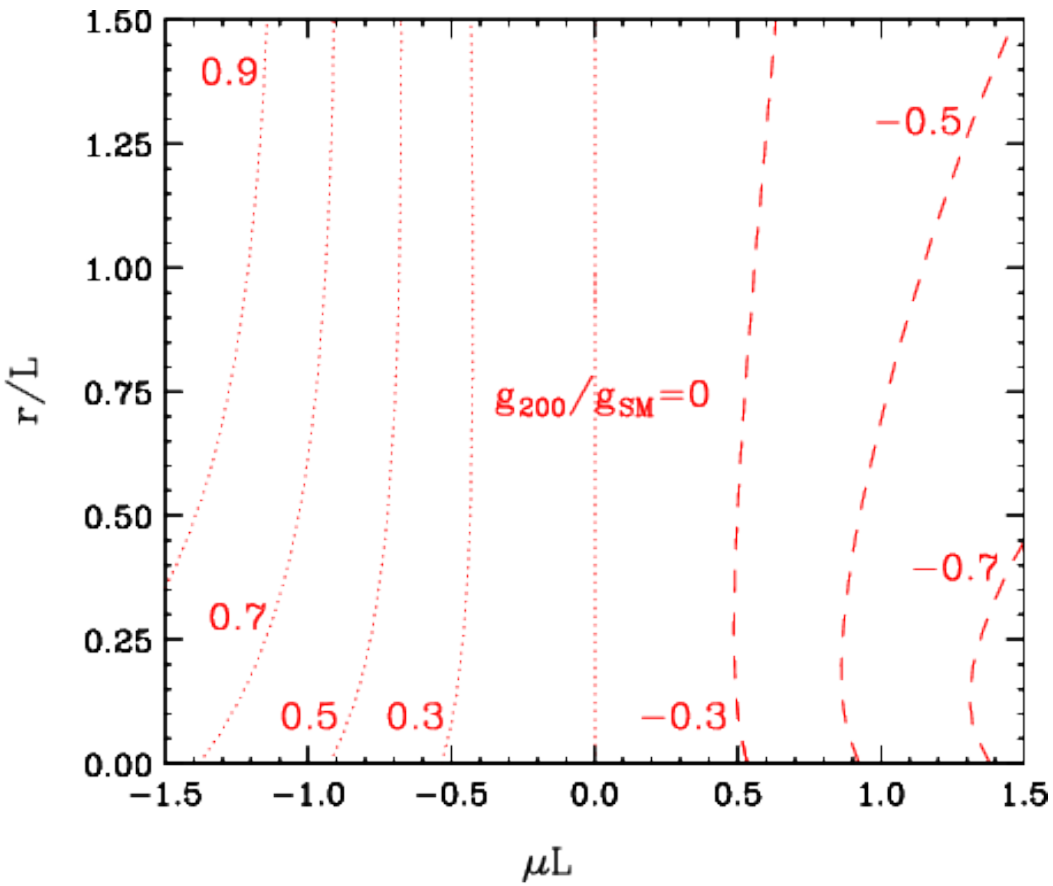
NMUED: couplings



KK2--SM fermion coupling enhanced

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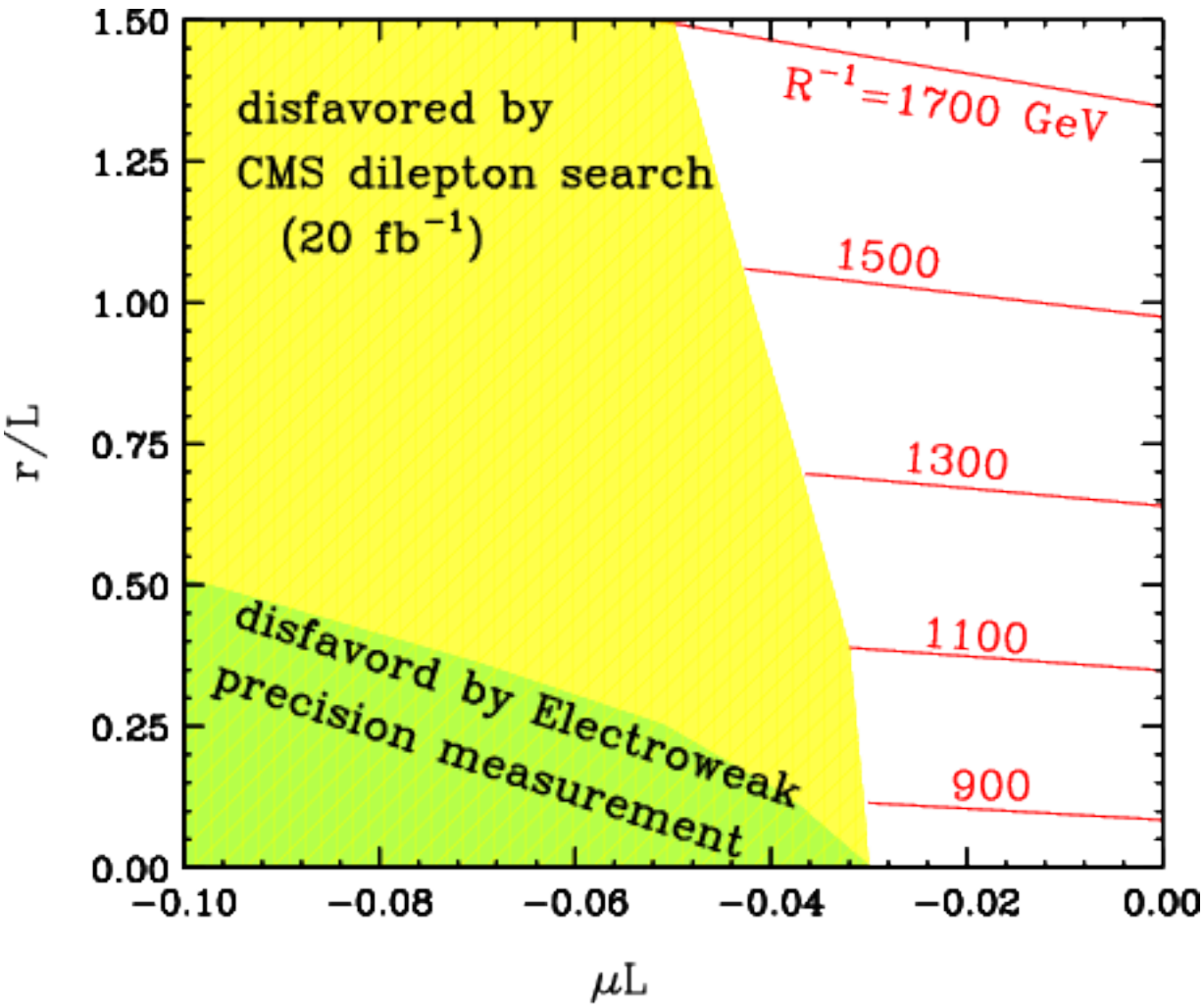
NMUED



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- For universal boundary and universal bulk mass

HF4: UED Benchmarks

- We propose the following:
  - Consider 5D UED only
    - 6D model needs to address an issue with DM (too low KK scale)
  - Minimal UED
    - two parameters: R and Λ (cutoff)
    - cutoff dependence: log(RΛ)
    - mass spectrum from radiative correction (no boundary terms)
    - Include Δ_{q1}, explore the connection with direct detection.
  - NMUED with brane terms for strong sector
    - two additional parameters: bulk mass term μ, boundary parameter *r*.
    - New signals: 2nd resonance ⇒ SM quarks, ...
  - Signatures (standard SUSY search + resonances)
    - level 1: jets + n-leptons + met, n=0,1,2,3,4
    - level 2: dijet, dilepton and lepton-neutrino final states

Please give suggestions, and in particular, offer your help!